VIRGINIA MINERALS

COMMONWEALTH OF VIRGINIA

DEPARTMENT OF MINES, MINERALS AND ENERGY
Richmond, Virginia

Published quarterly by the DIVISION OF MINERAL RESOURCES
900 Natural Resources Drive, Charlottesville, VA 22903

VOL. 43 FEBRUARY 1997 NO. 1

SEM and EMX Study of Titaniferous Minerals in the Ordovician Deicke K-bentonite of Southwestern Virginia

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INTRODUCTION

Numerous beds of altered volcanic ash known as potassium bentonites (K-bentonites) occur in Middle and Upper Ordovician strata of the Valley and Ridge province of Virginia and adjacent states (Haynes, 1992, 1994; Haynes and others, 1995, 1996). The heavy mineral fractions from two of the most widespread of these tephras, the Deicke and Millbrig K-bentonites of Rocklandian age, contain zircon, apatite, biotite, and, in many Deicke samples, hexagonal titaniferous grains. These minerals represent primary phenocrystic components that have remained chemically unaltered or which have been altered to varying degrees. In this paper we present findings from our investigation of the morphology, size, and composition of the phenocrystic titaniferous heavy minerals in the Deicke K-bentonite using scanning electron microscope (SEM) and electron microprobe (EMX) analyses. These titaniferous grains, which show relatively little variation in shape from locality to locality, vary greatly in texture and composition, from purplish black, nearly unaltered, weakly magnetic ilmenites to light brown, nonmagnetic grains of mixed anatase and rutile from which all iron has been leached.

LOCALITY AND SAMPLE INFORMATION

The Deicke K-bentonite has been identified and sampled at several well-studied sections of Ordovician strata throughout the southern Appalachians (Haynes, 1994). In the Valley and Ridge province of southwestern Virginia the Deicke is present throughout the Powell, Clinch, Holston, and New River Valleys (Haynes, 1992). The locations of nineteen exposures at which the Deicke K-bentonite is present and from which we obtained samples are shown in Figure 1 and are tabulated in the Appendix. Most of these exposures, which are in Virginia and nearby areas of West Virginia and Tennessee, have been described by Haynes (1992, 1994) and Haynes and Goggin (1993, 1994), but four sections (Millers Cove, Rockdell, Dodson Mountain, and Red House Branch) at which the Deicke has been identified only more recently are also included. Our samples from these localities are in the Department of Mineral Sciences collection at the National Museum of Natural History in Washington, DC. More detailed discussions of local and regional stratigraphic and structural relations, including a description of the stratigraphic interval in which the Deicke K-bentonite occurs, are in Haynes (1992, 1994) and Haynes and Goggin (1993, 1994).

With some effort in the field and the laboratory, small quantities (several hundred grains) of the phenocrystic heavy minerals in Deicke samples can be readily separated for study. The titaniferous minerals are largest and most abundant in the lower 10 to 20 centimeters of the Deicke. At the Harrogate, Hagan, Sewell Bridge, and Hurricane Bridge sections, all in the Powell Valley, this is a coarse sandy zone immediately above the bedded chert underlayer. At sections to the east this is just the lower 20 or so centimeters of the reddish brown bentonite rock that characterizes the Deicke in those sections. Samples from the lower half of the bed contain maximum amounts of the titaniferous minerals; throughout the southern Appalachians the volume of altered ilmenite in the Deicke decreases upsection, with a corresponding increase in biotite content in the bed. The relatively few biotite grains present in a Deicke sample are on average one-third the size of the abundant biotite grains in the more biotite-rich Millbrig, and they contain on average 1.5 to 2 % more TiO_2 than biotites from the Millbrig (Haynes and others, 1995).

At the Harrogate, Hagan, Hurricane Bridge, and Sewell Bridge sections the Deicke is in poorly fossiliferous gray micrites of the upper Eggleston Formation. It is a normally graded bed, with the coarsest material in a basal sandy zone. Although Deicke samples from cores and from deep cuts that are excavated well below grade such as the Hagan section are observed to be a grayish green color

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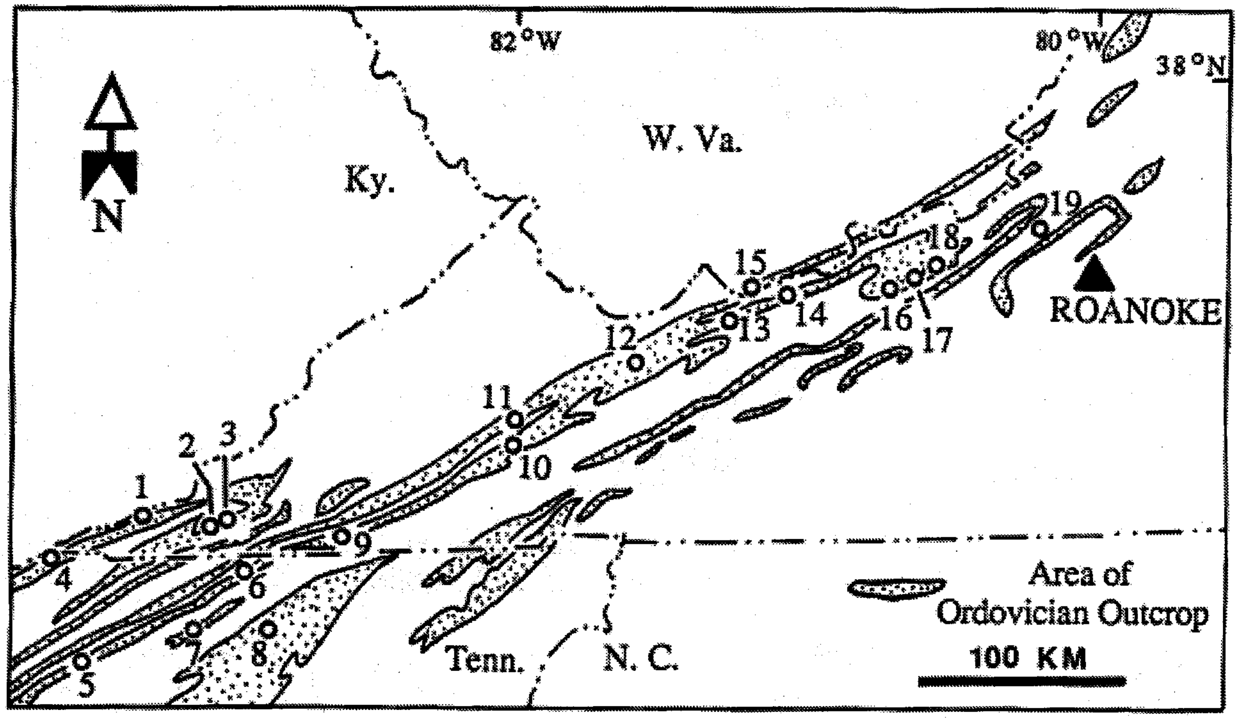


Figure 1. Location of 19 exposures in Virginia, West Virginia, and Tennessee from which titaniferous minerals in the Deicke K-bentonite can be obtained. Locality information is in the Appendix.

(5G 5/2), the more common color of the Deicke in Powell Valley sections — typically shallow and weathered roadcuts or railroad cuts at or near grade — is a grayish orange (10YR 7/4) to pale yellowish brown (10YR 6/2). This color, which characterizes samples even after much excavation into the outcrop, is the color of the mixed-layer illite/smectite that is the matrix of these altered tephras and is secondary after volcanic glass (Haynes, 1992). The Deicke is about one meter thick in the Powell Valley and it overlies a continuous layer of vitreous dark green to black chert several centimeters thick. This bedded chert occurs beneath the Deicke throughout the western Valley and Ridge from Virginia to Alabama (Haynes, 1992, 1994), and it can be a useful aid when attempting to locate the Deicke in hillside exposures such as the Sewell Bridge section. Although the chert is thick and superbly exposed at the Hagan, Sewell Bridge, and Gate City sections, it is thin at many other sections in the region and is not a reliable marker. A bedded chert layer very similar in appearance, although thinner, also occurs beneath the Millbrig K-bentonite, several meters upsection from the Deicke, at many sections in this region.

East of the Powell Valley the Deicke and the strata immediately adjacent to it pass through a significant facies change, with the drab olive and gray limestones of the Eggleston Formation grading into maroon and grayish red argillaceous limestones of the Moccasin and Bays Formations (Haynes, 1992, 1994; Haynes and Goggin, 1994). In all exposures in these outcrop belts, from Thorn Hill and Dodson Mountain in Tennessee northward to Goodwins Ferry and Millers Cove in Virginia (Figure 1), the Deicke varies in thickness from about 20 centimeters to one meter, and there is only a slight difference in color between it and the adjacent grayish red limestones and siltstones of the Moccasin or Bays Formations. In fact, where it occurs in the Moccasin or Bays Formations the Deicke is typically a moderate reddish brown color (10R 4/6) similar to the enclosing redbeds, and this color is the most striking textural change from its occurrence in the Eggleston Formation sections farther west. At the Thorn Hill, Eidson, and Dodson Mountain sections there is a light whitish gray sandy coarse zone at the base, in which the dark titaniferous grains can be seen without magnification, but at the other sections where the Deicke is in the Moccasin Formation redbeds it consists only of moderate reddish brown clayshale layers, with some yellowish brown coloration present as well. The red color is subordinate at the Millers Cove section, where the Bays Formation is more drab than grayish red in color (Bauerlein, 1966), and appears to us to be transitional between the Bays and Eggleston Formations (Haynes and Goggin, 1993, 1994). In some sections (e.g., Plum Creek, Rockdell, Trigg, Goodwins Ferry, Mountain Lake Turnoff) the Deicke occurs one to three meters upsection from a fine to medium grained to conglomeratic quartz arenite, the Walker Mountain Sandstone Member, and that unit can be a useful stratigraphic marker bed when one is attempting to locate the Deicke (Haynes, 1992; Haynes and Goggin, 1993, 1994). Although the Millbrig K-bentonite is present in the Bays Formation throughout Tennessee and Virginia, the Deicke is absent from the Bays at most exposures in the region, with the Citico Beach (Haynes, 1994), Dodson Mountain, and Millers Cove sections being the only exposures we know of at this time where the Deicke is present in strata that have been traditionally assigned to the Bays Formation.

SAMPLE PROCESSING

Because of the abundance of clay minerals in the Deicke K-bentonite, appreciable quantities of sample must be processed to obtain even a very small amount of heavy minerals for study, and a substantial amount of washing is necessary to remove the clay fines. Approximately 50 grams of sample will yield a heavy mineral fraction weighing only a few hundredths of a gram, but totalling several hundred individual grains, mostly the titaniferous grains but includ-

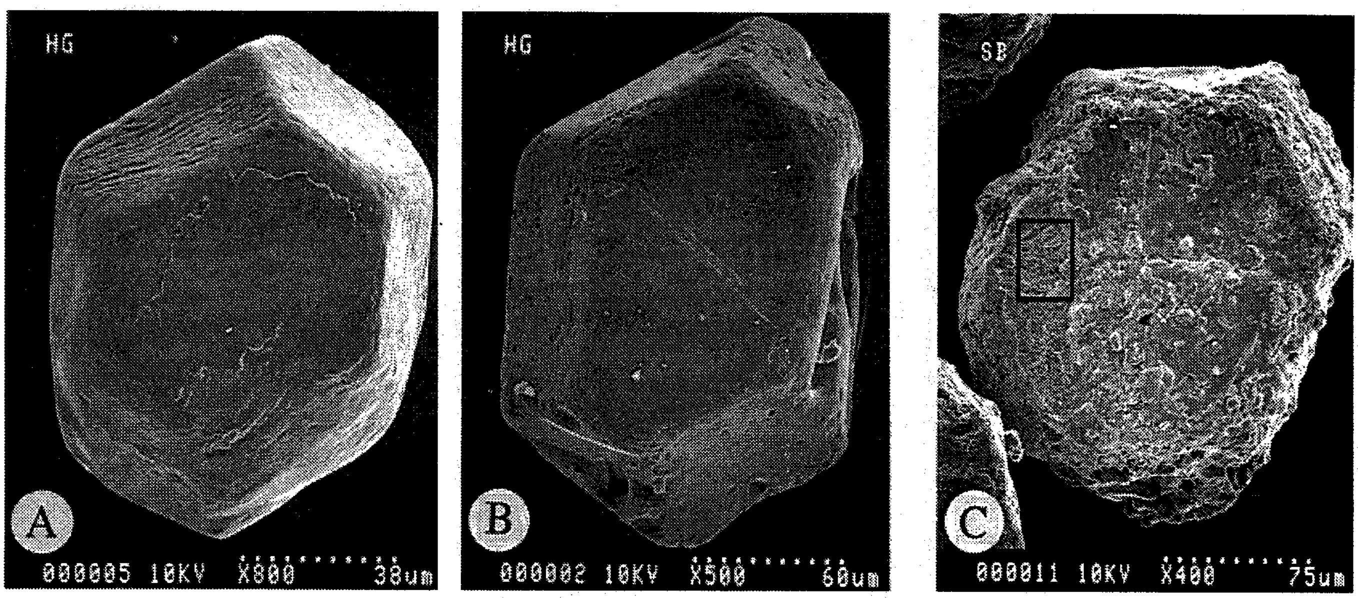


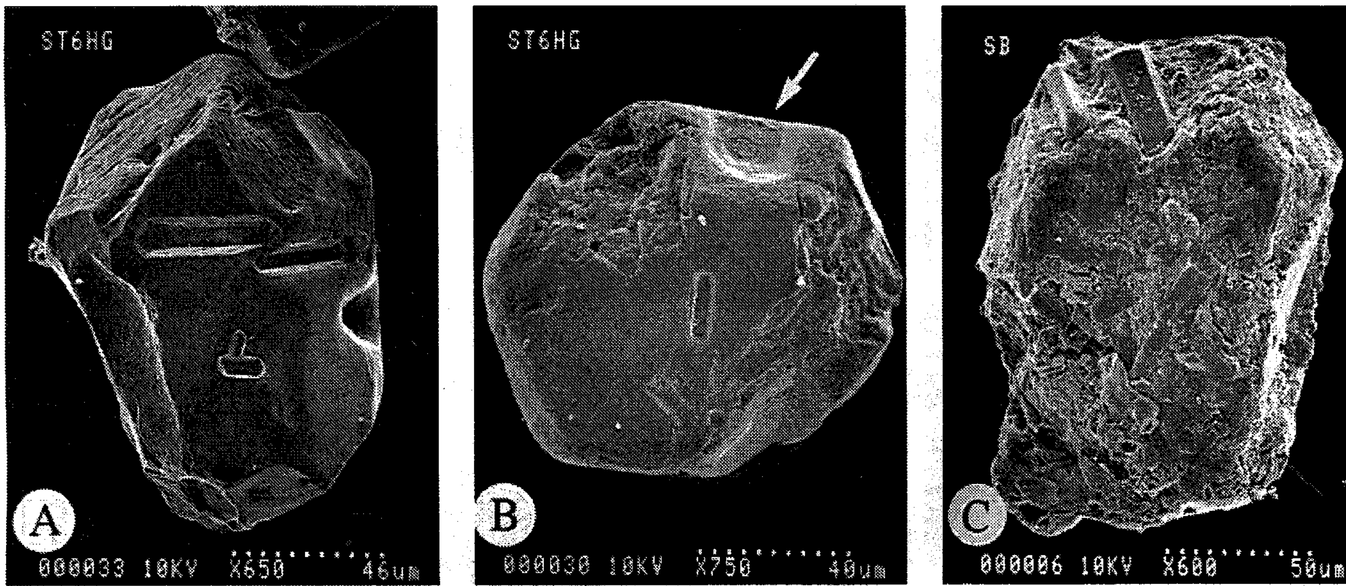
Figure 2. SEM photomicrographs showing the appearance of typical ilmenite and mixed anatase and rutile grains in the Deicke K-bentonite. Scale (in microns) is at lower right of all photomicrographs. **A.** Euhedral ilmenite grain from the Rockdell section showing subequilateral hexagonal form as outlined by the large basal plane {0001}. **B.** Euhedral ilmenite grain also from the Rockdell section. **C.** TiO_2 grain from the Sewell Bridge section. The original hexagonal shape is still evident, but recrystallization at the atomic level from a hexagonal mineral (ilmenite) to a tetragonal mineral (rutile and anatase) has resulted in an apparent "roughening" of the crystal faces. The outlined rectangular area is shown in D. **D.** Higher magnification of the area outlined on the TiO_2 grain in C. The pervasive leaching of iron from the original ilmenite and recrystallization to TiO_2 minerals has resulted in a porous structure that gives the appearance of being etched or pitted.

ing euhedral zircon and apatite. We process the samples as follows, with usually excellent results. Samples are first air dried and then crushed manually but non-vigorously into a powder in an agate mortar. This mixture is placed into a beaker of distilled water and thence into an ultrasonic bath for about five minutes. The resulting suspension is wet sieved through stacked 250 micron, 62 micron, and 38 micron stainless steel standard mesh sieves. The sieves are washed back into a beaker and the process is repeated one or more times until the water remains clear following sonification, an indication that the clay has been removed. The nonclay minerals retained on all sieves are then washed into watchglasses, with the bulk of the water pipetted away and the remainder evaporated to dryness. Separation into light and heavy fractions is achieved using a standard double-funnel heavy liquid setup; we use nontoxic, water miscible sodium polytungstate as the heavy liquid. Once the heavy minerals are collected on filter paper and thoroughly rinsed with distilled water to remove all heavy liquid, they are washed from the filter paper into a watch glass and dried.

TEXTURAL DESCRIPTION

Only about 100 to 300 microns in length, the titaniferous grains form the bulk of the heavy mineral fraction obtained from the coarse grained sandy zone present in the lower zone of the Deicke in the Powell Valley, or, in exposures in the Clinch and New River Valleys to the northeast, where that zone is absent, from the grayish red plastic clay to brittle mudrock that makes up the lower half of the bed. The euhedral shape of these non-equilateral hexagonal grains in samples from the 19 exposures is obvious at various levels of magnification, from the high power magnification of a scanning electron microscope (Figures 2 and 3) to the relatively low power magnification of a binocular microcope. The crystal faces, especially the large polygonal basal planes {0001} and {000}, are readily discerned, even on chipped or broken grains (Figure 3C). The form, which is characteristic of ilmenite, is a principal clue to the identity of these minerals.

When viewed under a binocular microscope at medium to high power, the color of the hexagonal titaniferous grains in Deicke



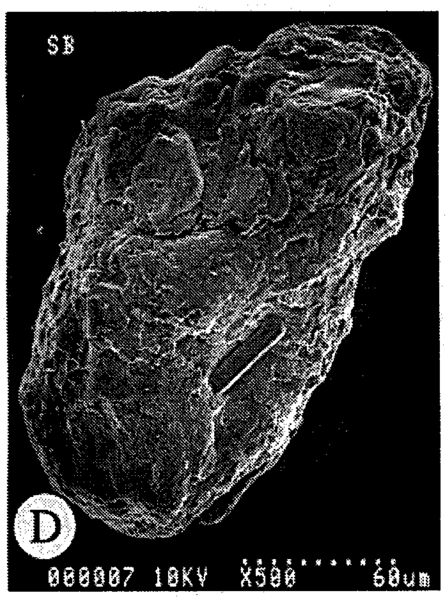


Figure 3. SEM photomicrographs showing characteristic features of ilmenite and mixed anatase and rutile grains in the Deicke K-bentonite. Scale (in microns) is at lower right of all photomicrographs. **A.** Ilmenite grain from the Rockdell section with four empty grooves (two large, two small) on the basal plane {0001}. **B.** Ilmenite grain also from the Rockdell section, with one small empty groove and one exceptionally large groove (arrow) that is the mold of the termination of a euhedral crystal. **C.** TiO_2 grain from the Sewell Bridge section with three apatite(?) crystals (arrows) embedded in the grain. **D.** TiO_2 grain also from the Sewell Bridge section with a single euhedral apatite(?) crystal protruding from the fine-grained TiO_2 matrix.

samples from the Moccasin or Bays Formation sections in outcrop belts east of the Powell Valley is a reddish black to purplish black. All the crystal faces, but especially the large basal plane surfaces {0001} and {000} have a smooth and highly reflective, almost mirror-like surface, giving the grains a metallic luster. These black grains take an excellent polish. In thin section they are opaque except for occasional grains that exhibit a deep reddish brown color around the edges when the condenser is in. When viewed with an SEM the relative smoothness of the crystal faces, noticeably the basal planes {0001} and {000}, is apparent (Figures 2A and 2B).

By contrast, the hexagonal grains in Deicke samples from the Eggleston Formation sections of the Powell Valley are uniformly a porcelaneous light brown (5YR 6/4); a caramel color. In thin section under reflected light these grains nearly always exhibit a pattern of needle-like projections extending in toward the center of the grain from the edge, and they take only a moderate polish. Under cross-polarized transmitted light these grains exhibit high-order red and green interference colors. When viewed with a binocular microscope the basal {0001} and {000} planes are observed to be poorly reflective to nonreflective, and those surfaces show a rough and pitted or etched texture, which is quite evident at the higher magnification of the SEM (Figures 2C and 2D) and is a striking contrast to the relatively smooth basal {0001} and {000} planes of the titaniferous grains from sections farther east.

Most of the reddish black and purplish black grains are moderately to weakly magnetic, without heating, but none of the caramel colored grains is magnetic under any conditions.

Many of these grains have a long, thin groove or grooves on the basal planes (Figures 3A and 3B). Examination with both the binocular and scanning electron microscopes reveals that in some grains a clear rodlike mineral is nestled in these broad basal {0001} and {000} planes (Figures 3C and 3D). The morphology of these grains suggests that they are apatites, which are moderately abundant in the heavy mineral separates, but because no such grain survived the thin-sectioning process still embedded in the titaniferous grains, electron microprobe analysis of an attached grain such as those in Figures 3C and 3D could not be carried out.

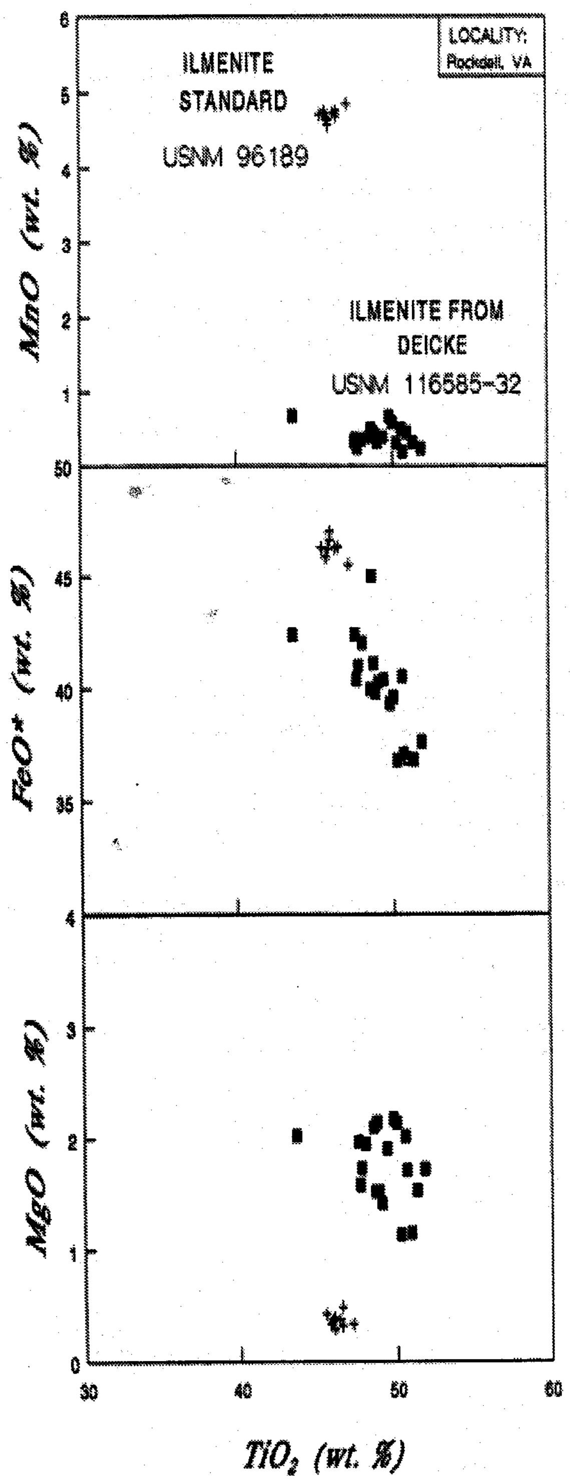


Figure 4. Major element chemical variation scatter plot diagrams for ilmenites in the Deicke K-bentonite from the Rockdell (Hayters Gap) section. Relative to the ilmenite sandard used to monitor analytical precision the Deicke ilmenites contain slightly less MnO and FeO* and slightly more MgO and TiO_2. Also, there is measurable compositional variation between individual Deicke ilmenites, suggesting that these grains may have been slightly altered chemically during diagenesis of the Ordovician sequence. Nonetheless, this alteration has not been sufficient to prevent recognition of the grains as primary ilmenites by their color, composition, and magnetic character.

COMPOSITION

The titaniferous grains present in the Deicke K-bentonite throughout the eastern midcontinent have been identified variously as ilmenite, anatase, rutile, TiO_2, and leucoxene (Samson and others, 1988; Haynes, 1992, 1994). From visual inspection of crystal textures, observation of magnetic character, and SEM and EMX analyses, we now identify the least altered of these grains as ilmenite (Figures 2A and 2B, 3A and 3B). And, based on the above criteria as well as preliminary X-ray diffraction analyses, we now identify the more altered grains as mixed anatase and rutile, but principally anatase, the low-temperature TiO_2 polymorph (Figures 2C and 2D, 3C and 3D). These TiO_2 grains are pseudomorphous after ilmenite from which all iron, both as Fe^{2+} and Fe^{3+}, has been leached.

Compositional data from EMX analyses of several of the magnetic titaniferous grains in our Deicke samples from the Rockdell section in Russell County are presented in Figure 4. Three bivariate scatter plots, of MnO, FeO (as total iron, FeO*), and MgO versus TiO_2, are shown. Included are the data points from repeated analysis of an ilmenite standard (USNM 96189 of Jarosewich and others, 1980) used to monitor analytical precision. It is evident from Figure 4 that the Deicke ilmenites from Rockdell, which represent the least altered of the many grains we analyzed, have less iron relative to the ilmenite standard, but given the variety of possible compositions in magmatic ilmenites because of solid solution in Fe-Mg-Mn space, it is possible that the Deicke ilmenites crystallized with less FeO* originally. The Deicke ilmenites from the Rockdell section also contain several percent less MnO but slightly more MgO than the ilmenite standard (Figure 4), so we believe that these volcanogenic ilmenites have always been compositionally different from the Smithsonian standard ilmenite. Some alteration may have in fact taken place, as the slightly low EMX analytical totals, nearly all of which total 93 to 95 %, suggest that a hydrous phase may be present. This could account for the slightly low analytical sums. Nonetheless on the basis of their crystal morphology, color, magnetism, and size, as well as their overall composition we consider these weakly magnetic grains to be ilmenites that may have been slightly altered during post-burial diagenesis.

The caramel colored titaniferous grains in Deicke samples from the Powell Valley have lost all their original iron and are compositionally now TiO_2, mostly anatase. Prior to leaching of all the iron it is possible that ilmenite may pass through an intermediate mineral phase, which is pseudorutile, $Fe_2Ti_3O_9$, a compositionally distinct intermediate alteration product between ilmenite and anatase or rutile. In pseudorutile all the iron in an ilmenite grain, originally present as Fe^{2+}, has been oxidized to Fe^{3+}, and about one-third of the total iron has been lost (Teufer and Temple, 1966; Grey and Reid, 1975). Although we have analyzed numerous grains we have not yet found any pseudorutile among the titaniferous grains of the Deicke K-bentonite.

IMPLICATION FOR DIAGENETIC HISTORY

The prevalence of redbeds in the Moccasin and Bays Formations is a testament to diagenesis in an oxic environment (Berner, 1981). The diagenesis of ilmenite in sedimentary sequences is discussed by Morad and AlDahan (1986) and Morad (1988), and Haynes (1994) proposed a diagenetic history for the titaniferous minerals in the Deicke throughout the southern Appalachians. Haynes (1994) recognized ilmenite in Deicke samples from the Colvin Mountain Sandstone of Alabama and Georgia, but was at that time unaware of the existence of ilmenite in Deicke samples from sections in the Moccasin and Bays Formations, the along-strike equivalents to the northeast of the Colvin Mountain Sandstone. In fact, part of the discussion in Haynes (1994) was based on the assumption that the only nonsilicate ferroan mineral in the Deicke from Moccasin Formation sections was hematite. As a result Haynes (1994) postulated an early diagenetic episode in the anoxic sulfidic environment of Berner (1981), possibly related to the complex diagenetic history of the limestones downsection from the Moccasin as inferred from study of cathodoluminescent patterns (Grover and Read, 1983). This was thought to have been followed by the pervasive and thorough oxidation of the Moccasin sediments.

From our more recent study of the occurrence and nature of the titaniferous grains in the Deicke we amend the interpretation of Haynes (1994) and add the following information regarding the likely diagenetic history of the Deicke in the eastern Valley and Ridge of Virginia. Because all samples of the Deicke from exposures in the redbeds of the Moccasin and Bays Formations contain ilmenite that, while slightly altered, is nonetheless still weakly magnetic without heating, it is evident that the original ilmenite phenocrysts survived regional diagenesis with little compositional change. Although zonation of carbonate cements in the limestones beneath the Moccasin and Bays Formations redbeds provides unequivocal evidence for the presence of anoxic pore waters during mid-Paleozoic time (Grover and Read, 1983), it now seems likely that the sediments of the Moccasin and Bays Formations were not widely subjected to these regionally reducing diagenetic conditions. On the contrary, diagenesis of the Moccasin and Bays Formations redbeds quite probably occurred under conditions similar to those experienced by the Colvin Mountain Sandstone of Alabama and Georgia, such that from the time of deposition until deep burial in the later Paleozoic the sediments were exposed principally to the oxic environment of Berner (1981). The absence of pyrite in the Moccasin and Bays redbeds supports this (Haynes, 1994), but a more definitive cathodoluminescence study of cements in the Moccasin Formation limestones would help to resolve uncertainties surrounding the diagenetic history of the Deicke in these redbed sequences.

APPENDIX: SAMPLE LOCALITY INFORMATION

Further geologic and geographic information about many of these localities (shown in Figure 1), including much additional discussion and cross-referencing of older reports that include earlier measurements of these and other sections, is provided by Haynes (1992, 1994) and Haynes and Goggin (1994). Additional stratigraphic information specifically about the Red House Branch section is in Ruppel (1979), about the Dodson Mountain section is in Hergenroder (1966), and about the Rockdell section is in Hergenroder (1966) and Kreisa (1980).

1. *Hagan*
Location: Exposure in high cut along the east side of the CSX railroad switchback adjacent to State Road 621 at Hagan, 1.5 km north of U.S. Highway 58. Permission must be obtained from CSX to visit this locality. Rose Hill 7.5' quadrangle, Lee County, Virginia.
Geologic Units: Deicke K-bentonite in the Eggleston Formation, USNM sample 116585-1.

2. *Hurricane Bridge*
Location: Exposure in low embankment along the northeast side of State Road 654 at the base of Wallen Ridge southeast of Hurricane Bridge over the Powell River. Hubbard Springs 7.5' quadrangle, Lee County, Virginia.
Geologic Units: Deicke K-bentonite in the Eggleston Formation, USNM sample 116585-2.

3. *Sewell Bridge*
Location: Exposure in embankment and small ravine with intermittent stream along the north side of State Highway 70 south of Jonesville and the junction of State Highway 70 and U.S. Highway 58, and about 1.5 km south (road mileage) of the bridge over the Powell River. Ben Hur 7.5' quadrangle, Lee County, Virginia.
Geologic Units: Deicke K-bentonite in the Eggleston Formation, USNM sample 116585-3.

4. *Harrogate*
Location: Exposure along the northeast side at the end of the deep cut along the dismantled CSX (ex-L&N) railroad right-of-way about 500 m (track mileage) southeast of the former grade crossing at Myers School. Middlesboro South 7.5' quadrangle, Claiborne County, Tennessee.
Geologic Units: Deicke K-bentonite in the Eggleston Formation, USNM sample 116585-33.

5. *Thorn Hill*
Location: Middle exposure of three long cuts in the Moccasin Formation along the east side of U.S. Highway 25E near the base of Clinch Mountain on the northwest slope, about 2 km east of the bridge over the Clinch River. Avondale 7.5' quadrangle, Grainger County, Tennessee.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-34.

6. *Eidson*
Location: Exposure in cut along the south side of State Highway 70 between Eidson and Rogersville near the base of Clinch Moutain on the northwest slope, about 2 km north of and downhill from Little War Gap. Kyles Ford 7.5' quadrangle, Hawkins County, Tennessee.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-35.

7. *Red House Branch*
Location: Exposure of overturned strata along the east bank of the Red House Branch embayment of Cherokee Lake (Holston River) beginning at the east end of the U.S. Highway 11W bridge over the embayment, about 2.2 km northeast of the junction of U.S. Higway 11W and Tennessee State Highway 66 (Flat Gap Road) at Mooresburg. Section is underwater when reservoir is full. Russellville 7.5' quadrangle, Hawkins County, Tennessee.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-21.

8. *Dodson Mountain*
Location: Exposure in large cut along the northeast side of the new alignment of State Highway 70 at the southwest end of Dodson Mountain, between Rogersville and Interstate Highway 81. McCloud 7.5' quadrangle, Hawkins County, Tennessee.
Geologic Units: Deicke K-bentonite in the Bays Formation, USNM sample 116585-52.

9. *Gate City*
Location: Exposure in north end of high cut at the west end of the Gateway Plaza parking lot on the south side of combined U.S. Highways23/58/421 in Gate City about 1 km north of Big Moccasin Gap in Clinch Mountain. Gate City 7.5' quadrangle, Scott County, Virginia.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-4.

10. *Rockdell (Hayters Gap)*
Location: Exposure in low weathered cut along the northeast side of the State Highway 80 about 1.5 km from the Clinch Mountain summit at Hayters Gap and about 1.7 km southeast of the junction with State Road 619 at Rockdell. Elk Garden 7.5' quadrangle, Russell County, Virginia.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-32.

11. *Rosedale*
Location: Exposure in cuts along the northeast side of old State Highway 80 up the embankment from the newer alignment, 2.3 km northwest of the intersection of State Highway 80 with U.S. Highway 19 at Rosedale. Elk Garden 7.5' quadrangle, Russell County, Virginia.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-12.

12. *Plum Creek*
Location: Exposure in cuts along the southeast side of State Highway 16 between Frog Level and Thompson Valley, along Plum Creek. Tazewell South 7.5' quadrangle, Tazewell County, Virginia.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-5.

13. *Cove Creek*
Location: Exposure in cut along the south side of State Road 614 at the first hairpin turn in the road below Crabtree Gap. Cove Creek 7.5' quadrangle, Tazewell County, Virginia.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-6.

14. *Rocky Gap*
Location: Exposure in cut along the southwest side of U.S. Highway 52 (Frontage Road) parallel to Interstate Highway 77 about 1.5 km south of Rocky Gap. Rocky Gap 7.5' quadrangle, Bland County, Virginia.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-7.

15. *Bluefield*
Location: Exposure in long cut along the south side of State Road 598 (formerly U.S. Highway 52) on the northwest slope of East River Mountain, about 2.5 km northwest of and downhill from the mountain summit crossing. Bastian 7.5' quadrangle, Mercer County, West Virginia.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-58.

16. *Trigg*
Location: Exposure in long, low cut along the northwest side of State Road 730 beginning at the junction with State Road 622. Staffordsville 7.5' quadrangle, Giles County, Virginia.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-8.

17. *Goodwins Ferry*
Location: Exposure in high cut along the southeast side of State Road 625 on the east bank of the New River about 500 m north of and uphill from the Norfolk Southern railroad grade crossing. Eggleston 7.5' quadrangle, Giles County, Virginia.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-9.

18. *Mountain Lake Turnoff*
Location: Exposures in long cut along the northeast side of westbound U.S. Highway 460 about 400 m east of the intersection with State Road 700. Eggleston 7.5' quadrangle, Giles County, Virginia.
Geologic Units: Deicke K-bentonite in the Moccasin Formation, USNM sample 116585-10.

19. *Millers Cove*
Location: Exposure in pasture about 80 m northeast of the intersection of State Roads 620 and 701 in Millers Cove. Permission from the landowner must be obtained to visit this locality. Glenvar 7.5' quadrangle, Roanoke County, Virginia.
Geologic Units: Deicke K-bentonite in the Bays Formation, USNM sample 116585-18.

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NEW RELEASES

Publication 144. Geology, natural gas, oil, and other mineral resources of Wise County, Virginia, by Jack E. Nolde, 38 pages, 8 figures, 7 tables, full-color geologic map showing location of oil and gas wells, scale 1:50,000. Price: $11.50

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